1.0 INTRODUCTION

An application for a *Modification of Designation of Adequate Water Supply* for future development of groundwater resources within and adjacent to the City of Flagstaff (Flagstaff) was submitted by Flagstaff to the Arizona Department of Water Resources (ADWR) on January 5, 2012 (ADWR, 2012a; Flagstaff, 2012) (DWR No. 41-9000002.0002) (hereafter referred to as the "Flagstaff Application"). A separate *Modification of Designation of Adequate Water Supply* for future groundwater development at Red Gap Ranch (RGR) was submitted by Flagstaff to ADWR on September 25, 2009 (Flagstaff, 2009) (DWR No. 41-9000002.0001) (hereafter referred to as the "RGR Application"). The RGR Application was approved by ADWR on January 7, 2011 (ADWR, 2011). While the intent of this report focuses on meeting ADWR's requirements for the Flagstaff Application, it also includes discussion and inclusion of a portion of the ADWR approved RGR groundwater demands. Also included in this impact analysis are all future ADWR approved and committed groundwater demands for the entire study area, as provided to AMEC Environment & Infrastructure, Inc. (AMEC) by ADWR in preparing this impact analysis (ADWR, 2011 though 2012).

The following are provided for additional reference related to Flagstaff's Community Water System Number, past and current ADWR Designations, ADWR Applications for Modifications of Designation, and ADWR's Analysis of Adequacy for RGR:

- Community Water System – ADWR No. 91-000086.0000.
- Original Designation, May 17, 1973 (prior to the RGR Analysis of Adequacy) – ADWR No. 40-900002.0000.
- 1st Application for Modification of Designation (for RGR) – ADWR No. 41-900002.0001
- RGR Analysis of Adequacy, January 7, 2011 – ADWR No. 43-700607.0000.
- Current (2nd) Application for Modification of Designation – ADWR No. 41-900002.0002

This report presents and documents the groundwater modeling impact analysis completed by AMEC in support of the Flagstaff Application. This report was prepared in a format following the guidance provided in ADWR's Assured and Adequate Water Supply Rules Arizona Administrative Code (A.A.C.) R12-15-701 through R12-15-730, and ADWR's *Final Substantive Policy Statement for Hydrologic Studies Demonstrating Physical Availability of Groundwater for Assured and Adequate Water Supply Applications* which pertains specifically to the Coconino multiple aquifer system (C Aquifer) (ADWR, 2008). To accomplish this task AMEC utilized, refined, and recalibrated the United States Geological Survey (USGS) Northern Arizona Regional Groundwater Flow Model (NARGFM) (Pool et. al., 2011) with hydrologic data specific to the Flagstaff and RGR areas through the year 2010. The term "Flagstaff Model" as referenced throughout this report, represents the updated and refined NARGFM. Following completion of the transient calibration (1910 through 2110), the Flagstaff Model was run under two different two 100 year population growth scenarios (Scenarios 1 and 2).

Figure 1.0-1 illustrates the area modeled in the Flagstaff Model. The area of interest that the Flagstaff Model focused on (hereafter referred to as the "Focused Study Area") is included on Figure 1.0-1. A close-up map of the Focused Study Area is provided as Figure 1.0-2.

Flagstaff is located within the south-central portion of the Colorado Plateau in the Little Colorado River (LCR) Plateau basin in Coconino County, Arizona. RGR is located approximately 10 miles south of the LCR, and approximately 40 miles east of Flagstaff. Flagstaff and RGR are located outside of an ADWR designated Active Management Area (AMA). Figure 1.0-3 provides a close up map of the Flagstaff area and includes; present day Flagstaff City limits; major interstates; prevalent surface water and topographic features; the two existing Flagstaff Wastewater Treatment Plants (WWTPs) (Rio De Flag and Wildcat Hill); and, the C Aquifer "groundwater divide" located just south-southwest of Flagstaff (Bills et. al., 2007).

In order to understand groundwater and surface water flow conditions for the purposes of fulfilling the Flagstaff Application, the NARGFM (Pool et. al., 2011) was modified by AMEC to include:

- Adjusting hydraulic conductivity (K) data;
- Refining grid spacing within the Focused Study Area;
- Simulating all model-wide "exiting uses", "issued demands", and "application demands" (the sum of which equal "total demand") as defined by ADWR (2008) for the period 1910 through 2010 (ADWR, 2011 through 2012);
- Simulating recharge from discharges to the Rio de Flag from treated waste water generated at the Wildcat Hill and Rio de Flag WWTPs;
- Simulating seepage at ULM and Lake Elaine;
- Changing from the Stream (STR) Package of MODFLOW (which was used in the NARGFM [Pool et. al., 2011]) to the MODFLOW River (RIV) Package of MODFLOW to simulate perennial reaches of streams;
- Adjusting river stage and conductance values;
- Correcting errors in the NARGFM pumpage files related to duplicate pumping wells;
- Adding all post-2005 ADWR registered "non-exempt" and "exempt" wells (model-wide) to the Flagstaff Model pumpage datasets;
- Adding all new Flagstaff wells that were constructed and operated post-2005;
- Adding pumpage from Flagstaff area private water providers, which include Doney Park, Kachina Village, Mountain Dell, and Forest Highlands; and,
- Adjusting the NARGFM assigned pumpage to all Flagstaff wells with data provided directly from Flagstaff to AMEC.

The Flagstaff Model was refined and calibrated to the following applicable American Society for Testing and Materials (ASTM) groundwater modeling guidelines (ASTM, 1999):

- Standard Guide for Application of a Groundwater Flow Model to a Site-Specific Problem (ASTM D5447-93);
- Standard Guide for Comparing Groundwater Flow Model Simulations to Site-Specific Information (ASTM D5490-93);
- Standard Guide for Defining Boundary Conditions in Groundwater Flow Modeling (ASTM D5609-94);
- Standard Guide for Defining Initial Conditions in Groundwater Flow Modeling (ASTM D 5610-94);

- Standard Guide for Conducting Sensitivity Analysis for a Groundwater Flow Model Application (ASTM D 5611-94);
- Standard Guide for Documenting a Groundwater Flow Model Application (ASTM D5718-95); and,
- Standard Guide for Calibrating a Groundwater Flow Model Application (ASTM D5891-96).

To maintain consistency with the NARGFM, AMEC utilized the MODFLOW-2005 code (Harbaugh, 2005) in conjunction with the software package Groundwater Vistas© Version 5.51, Build 7 (Rumbaugh and Rumbaugh, 2007) for the Flagstaff Model. Groundwater Vistas© is a pre and post-processing groundwater modeling environment for MODFLOW that solves for total head in aquifers based on known or calculated input parameters. These parameters include, but are not limited to: boundary conditions, hydraulic conductivity (K), and, aquifer stresses. The Figures produced and presented in this report were created using ArcGIS ESRI® Geographic Information System (GIS) and Aquaveo GMS® graphical interface. The Flagstaff Model runs on standard versions of MODFLOW-2000 and MODFLOW-2005, which are available from the USGS.

Following final calibration of the transient simulation period (1910 through 2010), the Flagstaff Model was run for 100 years (from 2010 through 2110) under two population growth Scenarios (Scenarios 1 and 2). Both Scenarios, and the results from the 100 year model simulations, are presented in this report.

2.0 REGIONAL GEOLOGY AND HYDROGEOLOGY

This Section focuses on geologic and hydrogeologic properties within the Focused Study area with particular attention on the Flagstaff and RGR areas, both of which are located within the southeastern portion of the Coconino Plateau (Figure 2.0-1). The Coconino Plateau is a sub-province of the Colorado Plateau south of the Colorado River in north-central Arizona (Hunt, 1967). A discussion of regional properties for the entire NARGFM domain can be found in USGS Scientific Investigations Report 2010-5180 (Pool et. al., 2011). The term “study area” in this section of the report refers to the entire Flagstaff Model domain.

2.1 Geology

The Coconino (C) Plateau has several physical characteristics that set it apart as a sub-province at the southern edge of the Colorado Plateau. Most of the 5,000 mile^2 Coconino Plateau extends above 5,000 feet in altitude and steep drops in altitude as a result of geologic structure, erosion, or both occur at all of the margins of the Coconino Plateau. The southern third of the Coconino Plateau is covered by volcanic rocks of the San Francisco and Mount Floyd Volcanic Fields. The interior of the Coconino Plateau is a Cenozoic upland composed of nearly flat-lying Paleozoic and younger consolidated sediments (Billingsley and Hendricks, 1989; Beus and Morales, 2003). Thickness of the consolidated sedimentary rocks ranges from about 5,000 to 8,000 feet from the northern end of the Coconino Plateau to the southern end of the Coconino Plateau, respectively.

The three primary hydrogeologic formations which are represented in the Flagstaff Model (listed in order of increasing depth and age) and discussed in this section of the report are: the Chinle, Moenkopi, and Kaibab Formations; the Coconino multiple aquifer system (C Aquifer), which includes the Toroweap Formation, the Coconino Sandstone, and the Upper and Middle Supai Formations; and, the Redwall-Muav Aquifer (R Aquifer), which includes the Lower Supai Formation (confining unit), Redwall-Muav Limestone, and Temple Butte Formation as well as the underlying crystalline rocks that are exposed at the land surface in the southern and eastern parts of the study area where the R Aquifer is absent (Figure 2.1-1).

The Coconino Plateau is composed of (listed in order of descending age) Precambrian basement granites and metamorphic rocks, layered Paleozoic and Mesozoic sedimentary rocks, Tertiary and late Cenozoic volcanic rocks, sedimentary rocks, and unconsolidated sediments, and Cenozoic to late Cenozoic unconsolidated sediments. Generalized stratigraphy of the Coconino Plateau is provided in Figure 2.1-2. Structurally the Coconino Plateau is characterized by large erosion escarpments and regional folds, faults, and other fractures that help to define the boundaries of the Coconino Plateau and further define the geologic framework (Bills et. al., 2007). The sedimentary rocks generally are flat lying to gently dipping. Regional dips are two degrees to the southwest in most of the Coconino Plateau, 1 degree to the northeast in the southwestern part of the Coconino Plateau, and 1 to 5 degrees to the east or northeast in the eastern and northeastern parts of the Coconino Plateau. The Cataract Syncline in the western part of the Coconino Plateau and the Little Colorado River (LCR) basin in the eastern part of the Coconino Plateau are structural and erosional low areas separated by the uplands of the Kaibab Uplift in the central part of the Coconino Plateau. The Mogollon Rim, the result of uplift and cliff erosion, is a prominent transition from the Coconino Plateau to the lower altitudes of Verde Valley.

2.1.1 Coconino Sandstone

The Permian Coconino Sandstone is a white to tan or light brown, crossbedded, aeolian, fine-grained sandstone. The Coconino Sandstone is about 700 feet thick along the Mogollon Rim but can be as thick as 1,100 feet near Flagstaff and 1,200 feet at the headwaters of the East Verde River. Exposures in the Grand Canyon indicates the formation ranges in thickness from 150 feet in the west to 500 feet in the eastern parts (Billingsley, 2000). Extensively fractured zones along faults are likely permeable and have the potential to yield large quantities of water. The Coconino Sandstone forms the primary part of the Coconino aquifer in the study area; however, the formation generally is above the water table west of Mesa Butte Fault. The Coconino Sandstone is equivalent to the Glorieta Sandstone and DeChelley Sandstone in western New Mexico (Pool et. al., 2011).

2.1.2 Supai Groups

The Supai Group consists of three formations: the Upper, Middle, and Lower Supai (Blakey, 1990). The formations date from the Upper Mississipian to the Lower Permian. The Upper Supai Formation is a complex series of horizontally bedded reddish to brown sedimentary units that are mostly fine-grained sandstone, siltstone, and mudstone. The Middle Supai Formation is grayish-orange, calcareous, very fine-grained sandstone to siltstone. The Lower Supai Formation is red to purple sandstone and siltstone, and gray limestone and dolomite. In some locations, the base of the formation contains conglomerate or breccia. The Supai Group in the Grand Canyon area is about 1,120 feet thick and generally thins eastward and south toward the Mogollon Rim (McKee, 1982; Billingsley, 2000). The Supai Group ranges from about 300 feet thick near Sedona to about 700 feet thick in other locations along the Mogollon Rim (Blakey, 1990). The Upper and Middle Supai Formation are more permeable than the Lower Supai Formation, and are included as part of the C Aquifer. The Lower Supai Formation generally acts as a confining unit to groundwater in the underlying R Aquifer, although sandstone intervals may be locally important water-bearing zones. In western New Mexico, the Supai Group is equivalent to the Yeso, Abo, Hermosa, and Molas Formations.

2.1.3 Redwall-Muav Limestone

The Mississippian Redwall Limestone is a massive, light-gray limestone and dark-gray to brown dolomite with thin beds and lenses of chert (Beus, 1989). McKee and Gutschick (1969) defined four members of the Redwall: the Whitmore Wash, Thunder Springs, Mooney Falls, and Horseshoe Mesa Members. All the members are found in outcrops along the south rim of Grand Canyon and at the southern and western margins of the plateau. Total thickness of the Redwall Limestone ranges from about 450 feet in the southeastern part of the study area to about 750 feet in the northwestern part (Beus, 1989; Billingsley et. al., 2006; Billingsley, 2000). In cuttings from wells throughout the study area, the Redwall Limestone is mainly a gray limestone with dolomite and, less commonly, chert. The formation lies unconformably on Devonian, Cambrian, or Precambrian rocks. In well cuttings, the upper part of the formation appears gradational with the Lower Supai Formation; however, significant pre-Supai erosion and weathering of the Redwall allows for intermixing of these two units at the contact (Beus, 1989; Billingsley and others, 2006).

2.2 Hydrology

Two large regional ground-water flow systems occur in the Coconino Plateau basin and adjacent areas: the C Aquifer and the R Aquifer. The C Aquifer occurs mainly in the eastern and southern parts of the 10,300-square-mile Coconino Plateau basin, and the R Aquifer underlies the entire study area (Bills et. al., 2007 [see Plate 3]). The C Aquifer is a water-table aquifer for most of its occurrence with depths to water ranging from a few hundred feet to more than 1,500 feet bgs. In the western part of the Coconino Plateau basin, the C Aquifer is dry except for small localized perched water-bearing zones decoupled from the C Aquifer to the east.

Cooley and others (1969) defined the C Aquifer as the sequence of rock units between the Kaibab Formation and the Supai Group (Figure 2.1-2). This definition has been refined to include the Kaibab Formation, Toroweap Formation, the Coconino Sandstone (and lateral equivalents, the DeChelly Sandstone and Glorieta Sandstone in New Mexico), the Schnebly Hill Formation, and the Upper and Middle Supai Formations (McGavock et. al,, 1986; Bills et. al., 2000; Bills and Flynn, 2002; Bills et al., 2007).

In the Flagstaff and RGR areas, the Permian Kaibab Formation is dominantly the exposed rock type. The younger fine-grained Triassic Moenkopi Formation is discontinuous in Flagstaff and more prevalent near RGR but still not a continuous unit. Stratigraphically younger than the Kaibab Formation in Flagstaff are Tertiary to Quaternary volcanic rocks that were deposited as flows over the Kaibab Formation and in some places the Moenkopi Formation. The primary water producing unit beneath Flagstaff and RGR is the Coconino Sandstone; however, the underlying Schnebly Hill Formation and Upper and Middle Supai Formations of the Supai Group have been found to be major water producing units (Figure 2.1-2). In the area of RGR, the Moenkopi Formation is more prevalent however not so much as to act as a confining layer. East and north of the LCR, where the Moenkopi is continuous, is where it acts as a true confining layer to the underlying C Aquifer (Bills et. al., 2007).

The Lower Supai Formation typically forms a confining unit that separates the Coconino aquifer from the underlying R Aquifer and local Proterozoic crystalline aquifers. West of the Mesa Butte Fault, the C Aquifer may be locally present but is largely unsaturated; the primary water bearing zones are the R Aquifer. The C Aquifer thins toward the east near New Mexico. The exact eastern boundary is uncertain, however, because water level and geologic data are insufficient. Groundwater in the C Aquifer is unconfined except where the base of the Moenkopi Formation falls below the potentiometric surface across much of the region north of the LCR.

The R Aquifer underlies the C Aquifer and ranges from at least 3,000 feet bgs in the western part of the Coconino Plateau basin to more than 3,200 feet bgs in the eastern part of the study area. The R Aquifer is a confined aquifer for most of its occurrence, with maximum hydraulic heads greater than 500 feet above the top of the aquifer in the western part of the study area, and greater than 2,000 feet above the top of the aquifer in the eastern part of the study area. In the eastern and northeast parts of the study area, the C Aquifer and the R Aquifer are in partial hydraulic connection through faults and other fractures.

Other aquifers and water-bearing zones in the NARGFM include the Big Chino aquifer and the Verde aquifer (commonly referred to as “basin-fill” aquifers) in the southern part of the study area and water-bearing zones in the Moenkopi and Chinle Formations in the central and northeastern part of the study area (Bills et. al, 2007). The C Aquifer, R Aquifer, and the basin-fill aquifers are the primary aquifers in the NARGFM.

3.0 MODEL DEVELOPMENT

3.1 Conceptual Model Development

The boundaries of the Focused Study Area of the Flagstaff Model are provided in Figure 1.0-2. Identification of the Focused Study Area included input from hydrologists Mr. Brad Hill (Flagstaff), Mr. Don Bills (USGS), Mr. Peter Mock (Peter Mock Groundwater Consulting, Inc.), and Mr. Abe Springer (Northern Arizona University). The Focused Study Area includes approximately: the western quarter of LCR Plateau basin; the eastern quarter of the Coconino Plateau basin; the northern half of the Verde Valley sub-basin; the upper quarter of the Tonto Creek basin; and, the northwestern tip of the Salt River Canyon sub-basin (Figure 2.0-1). Boundaries for the Focused Study Area within the Flagstaff Model were chosen based on hydrogeological and structural conditions, not basin or sub-basin boundaries as was done with the NARGFM.

Boundaries for the conceptual Flagstaff Model include: the Mesa Butte Fault to the north and northwest; the Diamond Rim Fault to the south and southwest; the LCR to the east; and, the Mogollon Rim (roughly equivalent to the groundwater divide between the Verde sub-basin and the LCR basin) to the south (Figure 3.1-1). While the Flagstaff Model covers the same extents as the NARGFM domain, the Focused Study Area represents an area around Flagstaff where the NARGFM grid was refined, and where Flagstaff and RGR modeling features were added to supplement features already present in the NARGFM.

3.2 Conceptual Water Budget

A visual depiction of the conceptual water budget for the Flagstaff Model is provided in Figure 2.1-1. As previously stated in **Section 3.1**, the Focused Study Area includes portions of several different basins and/or sub-basins within the NARGFM. Because the NARGFM water budgets are basin and sub-basin dependant, a comparison of model domain-wide water budgets at the end of 2005 (corresponding to the end of the NARGFM transient calibration) was made between the Flagstaff Model and the NARGFM. This was done following the transient calibration of the Flagstaff Model to evaluate impacts of NARGFM modifications to the inflow and outflow water budget components of the calibrated Flagstaff Model. **Section 3.6.5** provides additional discussion on this subject, including a numerical comparison of water budgets between the Flagstaff Model and the NARGFM.

3.3 Model Construction

3.3.1 Numerical Model Domain

The Flagstaff Model utilized the MODFLOW model files from the NARGFM (Pool et. al., 2011) as a starting point. For consistency with the NARGFM, the MODFLOW-2005 code (Harbaugh, 2005) was selected to simulate groundwater flow. The Flagstaff Model domain is the same as the NARGFM. The Flagstaff Model domain and grid are provided on Figure 3.1-1. As discussed in **Section 3.3.2**, the NARGFM grid was refined in the Flagstaff Model within the Focused Study Area.

3.3.2 Model Grid Discretization

The spatial coordinate system for the Flagstaff Model grid is NAD27 Universal Transverse Mercator, Zone 12 North. Horizontal and vertical units of the grid are in meters. The model grid origin is located at 660,000 meters (2,165,354 feet) easting and 3,580,000 meters (11,745,407 feet) northing. The grid is rotated 60 degrees clockwise to correspond with the regional geological structure and regional groundwater flow, as in the NARGFM (Pool, et. el., 2011). The elevation of the grid ranges approximately from 550 meters to 2,750 meters (1,805 to 9,022 feet).

The NARGFM used a uniform grid of cells measuring 1,000 by 1,000 meters (3,281 by 3,281 feet). The Flagstaff Model uses the NARGFM uniform grid with an added refinement to 250 by 250 meter (820 by 820 feet) cells within the Focused Study Area (Figure 3.1-1). The Flagstaff Model contains 796 rows and 617 active columns. Data quality checks were performed after the grid refinement step was completed to evaluate impacts on the resulting water level elevations (WLEs) within the Focused Study Area. This was done to evaluate the impact of the grid refinement on the resulting WLEs, so that the starting head conditions (end of 2005/beginning of 2006) could be assessed before proceeding with additional modifications of the NARGFM.

The data quality checks indicated relatively small differences in simulated versus observed WLEs, ranging from approximately three to 160 feet within the Focused Study Area, to as much as 300 feet outside of the Focused Study Area (most of which occurred at or near the boundaries of the Focused Study Area). The WLE differences are attributed to increased pumping and artificial recharge in the Flagstaff Model, and refined grid resolution (smaller model cells within the Focused Study Area), which causes relatively steep and variable gradients in WLEs between adjacent model cells. The differences were small enough to warrant additional modifications of the NARGFM, as documented in later sections of this report.

Model layering in the Flagstaff Model was obtained from the NARGFM datasets (Pool, et. al., 2011). No changes in model layering were made in the Flagstaff Model. Consistent with the NARGFM, the Flagstaff Model uses three layers to represent the hydrogeologic units that include sedimentary, carbonate rocks, and crystalline rocks. The unit represented by each model layer varies by location within the Flagstaff Model. The Flagstaff Model layer elevations and aerial extent are shown in Figures 3.3.2-1 through 3.3.2-4: Figure 3.3.2-1 shows the top of model layer 1; Figure 3.3.2-2 shows the top of model layer 2; Figure 3.3.2-3 shows the top of model layer 3; and, Figure 3.3.2-4 shows the bottom of model layer 3. Layer thicknesses are shown on Figures 3.3.2-5, 3.3.2-6, and 3.3.2-7, for model layers 1, 2, and 3, respectively.

The following is a summary of the primary geological units associated with the three layers in the Flagstaff Model:

- **Model Layer 1:** Represents the Chinle, Moenkopi, and Kaibab Formations; and, the underlying Upper Coconino Sandstone. The Upper Coconino Sandstone is locally confined where covered by the Moenkopi and/or Chinle Formations (e.g., east of the LCR), and unconfined where it is not (e.g., at RGR). The western extent of model layer 1 is roughly defined by the LCR in the eastern most portion of the Focused Study Area

(Figure 3.3.2-5) and thins to the west within a swath of about 10 miles of the LCR from Leupp to south of Winslow.

- **Model Layer 2:** Represents the Lower Coconino Sandstone and the Upper and Middle Supai Formations on the Colorado Plateau (the primary C Aquifer in the Flagstaff and RGR areas); the sand and gravel deposits in the Verde and Big Chino Valleys; and, the lower volcanic unit in the Little Chino and Upper Agua Fria sub-basin. Model layer 2 covers approximately 80% of the Focused Study Area, extending from about the eastern edge of the model domain to just past the Mogollon Rim to the west (Figure 3.3.2-6). Spatially the C Aquifer of the Colorado Plateau spans the majority of model layer 2; however, it does not occur south of the Mogollon Rim escarpment. Model layer 2 represents the primary aquifer for Flagstaff's existing production wells, including those drilled at RGR and future planed production wells at RGR.

- **Model Layer 3:** Represents the Redwall-Muav Limestone (R Aquifer) and underlying crystalline rocks that are exposed at the land surface in the southern and eastern parts of the study area where the C Aquifer is absent (Figure 3.3.2-6). Layer 3 extends across the entire Flagstaff Model domain (Figure 3.3.2-7).

3.3.3 Model Boundaries

The active domain for the Flagstaff Model is the same as the NARGFM (Pool et. al., 2011). Like the NARGFM, the model domain boundaries in the Flagstaff Model are aligned with watershed boundaries coincident with low-permeability crystalline rocks in the Verde River and adjacent basins, including the Truxton Wash, Trout Creek, Burro Creek, Tonto Creek and part of the Upper Agua Fria Sub-basin, and groundwater divides within the Colorado, Little Colorado and Salt Rivers Basins. Therefore, no-flow boundary conditions were used at the edges of the Flagstaff Model. The Focused Study Area is much smaller than the Flagstaff Model domain; however, this area of interest was not cut-out from the bigger model in order to prevent boundary impacts within the Focused Study Area.

3.4 Model Input Parameters

Material parameters defined in the Flagstaff Model include K; specific storage; specific yield; the stage, bottom elevation and sediment bottom thickness of the modeled reaches of river segments; model layer elevations and thicknesses (total and saturated); groundwater pumping, natural recharge from precipitation; artificial recharge (i.e., WWTPs, golf courses, irrigated farm lands, etc.); and, natural recharge from lake seepage and losing rivers, streams, and springs. The Flagstaff Model takes a conservative approach and does not include the on-going recharge from Lower Lake Mary and Walnut Creek.

3.4.1 Initial Conditions

Calibration of the Flagstaff Model was achieved through a transient calibration from 1910 through 2010, with the starting conditions (hydraulic heads) set equal to the Flagstaff Model output hydraulic heads at the beginning of 1910. This is automatically achieved in MODFLOW by creating the first stress period as “steady-state” with the remaining stress periods as transient (Flagstaff Model stress periods are discussed in **Section 3.5**).

3.4.2 Hydraulic Conductivity (K)

The Flagstaff Model initially used K values from the NARGFM (Pool et. al., 2011). These values were then changed during calibration to better match target WLEs and known conditions within the Focused Study Area. Figures 3.4.2-1, 3.4.2-2 and 3.4.2-3 present the final calibrated Flagstaff Model K distribution zones for each model layer. Table 3.4.2-1 provides the respective values for horizontal Ks (Kx and Ky) and vertical Ks (Kz). Some of the K zones in the NARGFM were also subdivided to obtain adequate WLE calibration. The anisotropy in all three directions (X, Y, and Z) in the Flagstaff Model are different from one another as was done with the NARGFM (Pool, et. al., 2011) to represent faulted regions.

A comparison of NARGFM versus the final calibrated Flagstaff Model for Kx and Ky is included in Table 3.4.2-1. All modified K values in the final calibrated Flagstaff Model are within one order magnitude of the NARGFM K values. The calibrated K values in the Focused Study Area are also in the close agreement with K values representing the same geologic units simulated in other numerical groundwater models (AMEC, 2009; Colley et. al. 1969; Leake et. al., 2005; Pool et. al., 2011; S.S. Papadopulos & Associates, Inc., 2005) and published K values in various reports encompassing some of the same geographic regions (Bills et. al., 2007; Bills et. al., 2000; Hart et. al., 2002; Mann, 1979; Hoffman et. al., 2006; Navajo Nation Department of Water Resources, 2000).

3.4.3 Recharge

Groundwater recharge in the Flagstaff Model occurs as result of natural recharge from precipitation (Figure 3.4.3-1); artificial recharge from man-made structures or practices (i.e., WWTPs, golf courses, irrigated farm lands, etc.), and natural recharge from lake seepage (Figure 3.4.3-2); and, natural recharge from losing rivers, streams, and springs (Figure 3.4.3-3).

Natural Recharge (Precipitation)
Natural recharge to the Flagstaff Model is the same as the NARGFM (Pool, et. al., 2011), which used the Basin Characterization Model (BCM) developed by Flint and Flint (2008) and isotopic analyses developed by Blasch and Bryson (2007). The BCM estimates monthly runoff, evapotranspiration (ET) rates, and direct infiltration for about 300 meter square grid cells across the western United States and considers multiple parameters that influence recharge such as rainfall, snowfall, solar radiation, wind speed, vegetation, soils, aspect, slope, temperature, humidity, and rock type (Flint and Flint 2008). Average-annual BCM estimated recharge rates from 1971 to 2005 were used to estimate average-annual recharge rates for the predevelopment period. Scaled decadal variations in recharge were estimated by using an extended BCM dataset for the period 1940 through 2005. Scaled variations in decadal recharge are similar to variations in precipitation and ranged from 1.0 inches per year for the predevelopment period, to 0.60 inches per year for the 1950s, 1.6 inches per year for the 1970s, and 0.7 inches for 2000 through 2005 (Pool, et. al., 2011).

The distribution array for natural recharge simulated in the calibrated Flagstaff Model for stress period 10 (2000 through 2005) is presented in Figure 3.4.3-1. The natural recharge rates from stress period 10 (2000 through 2005) were used for stress periods 11 through 15 (2006 through 2010) (Flagstaff Model stress periods are discussed in **Section 3.5**).

Artificial Recharge

Recharge features and rates from WWTPs, golf course water applications, and agricultural return flow within the Flagstaff Model are the same as the NARGFM (Pool, et. al., 2011), with the exception of the following additional recharge features:

- Recharge from discharges to the Rio de Flag from treated waste water generated at the Wildcat Hill and Rio de Flag WWTPs; and,
- Seepage from ULM and Lake Elaine.

Figure 3.4.3-2 provides a map showing these additional artificial recharge features. Artificial recharge was simulated in the Flagstaff Model using the MODFLOW Well Package. All other recharge features from the NARGFM datasets were interpolated forward from the beginning of 2006 through the end of 2010. It should be noted that while recharge data for the Prescott Airport Recharge Facility and Prescott Valley waste water treatment plant (WWTP) were included in the NARGFM datasets (Pool, et. al., 2011), location data for both facilities was not. Both were added to the Flagstaff Model based on aerial photos obtained from Google Earth®.

The Flagstaff Model takes a conservative approach and does not include the on-going recharge from Lower Lake Mary and Walnut Creek.

<u>Rio de Flag Recharge</u>

The Wildcat Hill and Rio de Flag WWTPs began discharging portions of their treated water within sections of the lower reach of the Rio de Flag Wash in 1986 and 1993, respectively. Discharges currently continue as water treated from both WWTPs exceeds user demand throughout the year. Discharge data for the period 1986 through 2010 for treated water generated at the Wildcat Hill WWTP was assigned to a segment of the lower reach of the Rio de Flag based on data provided by Flagstaff (Flagstaff, 2009 through 2012). This area in the Flagstaff Model is identified as the “Wildcat WWTP Recharge Area” (Figure 3.4.3-2). Discharge data for the period 1993 through 2010 for treated water generated at the Rio de Flag WWTP was assigned a different segment of the Rio de Flag based on data provided by Flagstaff (Flagstaff, 2009 through 2012). This area in the Flagstaff model is identified as the “Rio de Flag WWTP Recharge Area” (Figure 3.4.3-2).

The quantity of water available for recharge to each WWTP “Recharge Area” was reduced by five percent (%) of the discharged volume to account for ET. This value is based on a 2009 Rio de Flag ET study conducted by Flagstaff (Carson, 2009). The Rio de Flag WWTP and Wildcat Hill WWTP simulated discharges within the Rio de Flag Wash in the calibrated transient Flagstaff Model are summarized in Table 3.4.3-1.

Upper Lake Mary (ULM) Recharge

Simulated seepage rates for ULM in the calibrated transient Flagstaff Model were calculated from Flagstaff's estimated storage, production, and evaporation data for ULM for the period 1960 through 2010 (Flagstaff, 2009 through 2012) (Flagstaff, 2011b). All data and calculations referenced below are detailed in Table 3.4.3-2. A summary of the model simulated seepage rates for ULM is provided in Table 3.4.3-3.

"Total Yearly Loss (acre feet per year [af/yr])" (N) was calculated as follows:

1. "Highest Level Spring %" (B) – "Lowest Level October-April %" (D) = "Total Yearly Loss %" (G)
2. "Surface Water Prod (million gallons [MG])" (H) ÷ 100% storage capacity for ULM (MG)[1] = "Surface Water Production Loss of Lake %" (I)
3. "Total Yearly Loss %" (G) – "Surface Water Production Loss of Lake % (I) = "Evap Loss of Lake %" (J)
4. "Total Yearly Loss (MG/yr)" (M) = "Total Yearly Loss %" (G) * 100% storage capacity for ULM (MG)[2]
5. "Total Yearly Loss (af/yr)" (N) was then converted to MG/yr to obtain the "Total Yearly Loss (MG/yr)" (M).

It should be noted that the "Total Yearly Loss %" (G) values calculated by Flagstaff (Flagstaff, 2009 through 2012) (Table 3.4.3-2) attribute all loss to surface water production (H) and evaporation (J). According to a study done by Blee (1988), approximately 45% of "total outflow" from ULM is attributed to seepage. Based on this estimate, the simulated seepage rates for the calibrated transient Flagstaff Model were calculated as follows:

- "Total Seepage (af/yr)" (P) = "Total Yearly Loss (af/yr)" (N) * 45%

Flagstaff did not keep lake level records for ULM prior to 1960. Therefore, the 1960 calculated seepage rate of 2,261 af/yr was used for the period 1949 (the year ULM construction was completed) through 1959 (see Tables 3.4.3-2 and 3.4.3-3).

Lower Lake Mary Recharge

Although Flagstaff has taken a conservative approach by not including the substantial recharge from Lower Lake Mary and flows into Walnut Creek as part of the Flagstaff Model, it should be noted that ULM was created because the fractured bottom of Lower Lake Mary could not hold a significant long-term reliable surface water supply to meet growing demands. Lower Lake Mary continues to recharge water to the aquifer (Blee, 1988), as well as outflow from the Lower Lake Mary dam into Walnut Creek.

[1]A 100% storage capacity volume of 5,091 MG was used for reporting years prior to 2007 (Harshbarger and Preisler, 1972 – page 4-6), and 5,320 MG for reporting years after 2007 (Hornewer and Flynn, 2008 – Table 1).
[2]See previous footnote.

Lake Elaine Seepage

Simulated seepage rates for Lake Elaine were calculated for the years 1991[3] through 2010 using an estimated constant lake volume over the history of the lake. There were two reported volumes available for Lake Elaine; one with the water level at its spillway (equating to a lake volume of 473 acre feet), and one with the water level eight feet below its spillway (equating to a lake volume of 283 acre feet) (Turner Engineering Inc., 1990). Due to a lack of historical (long-term) "outflow" records for Lake Elaine, the average lake volume was assumed to be equal to its estimated volume at the lower (more conservative) level of eight feet below its spillway (equating to a lake volume of 283 acre feet). A discounted seepage rate of 35% (as compared to 45% for ULM) was then applied to Lake Elaine's average volume of 282 acre feet to obtain an annual seepage rate of 99 af/yr (Table 3.4.3-3).

Recharge to Rivers and Streams

Recharge to the groundwater system via rivers and streams were simulated using the MODFLOW River (RIV) Package (which allows for losing and gaining reaches to be simulated). Parameterization of this interaction is detailed in a later section (see **Section 3.4.5**).

3.4.4 Storage

Storage coefficient and specific yield are both significant storage terms that affect transient simulations. The storage coefficient and specific yield values in the Flagstaff Model are the same as those used in the NARGFM (Pool, et. al., 2011). The storage coefficient for model layers 1, 2 and 3 are 1 x 10^{-5} feet^{-1}, 1 x 10^{-4} feet^{-1}, and 1 x 10^{-6} feet^{-1}, respectively. Specific yield ranges from 0.05 to 0.15 for model layer 1, and from 0.06 to 0.25 for model layer 2. The specific yield for model layer 3 is 0.01.

The unconfined storage conversion option of MODFLOW was used for the transient drawdown simulations. This option uses the specific yield in unconfined portions of the aquifer, and the storage coefficient in confined regions of the aquifer, to provide the associated storage within the aquifer.

3.4.5 Rivers, Streams, and Springs

The Flagstaff Model simulated the same set of rivers, streams, and springs (Figure 3.4.3-3) as those simulated in the NARGFM (Pool et. al., 2011). Ephemeral stream reaches simulated in the NARGFM using the Drain (DRN) Package of MODLFOW were also simulated in the Flagstaff Model using the DRN Package of MODLFOW. Perennial stream reaches simulated in the NARGFM using the MODFLOW STR Package were simulated in the Flagstaff Model using the MODFLOW RIV Package. The switch in Packages for these perennial features was done because stream-flow accounting was performed in the Flagstaff Model as a post-processing step through Groundwater Vistas© (Rumbaugh and Rumbaugh, 2007) on the various river reaches that were identified as stream-flow targets to the Flagstaff Model. This switch of packages was performed because the sequential node ordering of streams was disrupted with the grid refinement of the Flagstaff Model and therefore the subdivided stream segments were no longer compatible with the MODEFLOW Stream Package. The disruption of node ordering

[3]Lake Elaine was reportedly constructed in 1991 (Tuner Engineering Inc., 1990).

eliminates the ability of the STR Package to route flow and pre-processing software (e.g., Groundwater Vistas©) to automatically fix this issue upon rediscretization. Use of the RIV Package neglects to do this accounting which can instead be performed directly within Groundwater Vistas© as post-processing. This was deemed appropriate for the scale of the Flagstaff Application objectives rather than sequentially renumbering the entire stream system of the NARGFM, or trimming stream cells and re-computing equivalent leakances for all stream segments, thus allowing the Flagstaff Model to achieve the same objective. River stage and conductance values for the Flagstaff Model were initially taken from the NARGFM (Pool et. al., 2011). These values were adjusted during calibration of Flagstaff Model during the head calibration (WLE "matching") process (see **Section 3.6.2**).

3.4.6 Evapotranspiration (ET)

ET parameters in the Flagstaff Model were the same as those used in the NARGFM (Pool et. al., 2011). ET of groundwater occurs only near stream channels where depths to water are shallow. Rates of ET from the groundwater system are a minor water-budget component at basin and regional scales.

Following what was done in the NARGFM, the ET surface for the Flagstaff Model was estimated at 3.28 feet below the minimum altitude of the land surface in each model cell (Pool et. al., 2011). Maximum depths for ET were assumed to be 16.4 feet. Maximum rates of ET ranged from 4.92×10^{-4} feet per day (ft/d) in most of the simulated ET areas, to 6.56×10^{-4} ft/d in areas near the Verde River and lower parts of tributary streams.

As previously discussed in **Section 3.4.3**, the quantity of water available for recharge to the Rio de Flag and Wildcat Hill WWTP "Recharge Areas" was reduced by 5% of the discharged volume to account for ET. This value is based on a 2009 Rio de Flag ET study conducted by Flagstaff (Carson, 2009).

3.4.7 Pumping Wells

Pumping wells in the Flagstaff Model were simulated using the MODFLOW Well Package. Pumping data was assembled for three pumping datasets: ADWR "non-exempt" wells, ADWR "exempt" wells, and future ADWR "issued" demands (ADWR, 2011 through 2012). All pumping wells simulated in the Focused Study Area are shown on Figure 3.4.7-1.

ADWR Non-Exempt Wells

Raw data for all ADWR non-exempt wells for the period 1910 through 2005 were obtained from the NARGFM pumpage datasets. During AMEC's review of this data, redundancy (duplicate wells) and missing ADWR 55 Database Registry Well Identification Numbers (55 No.'s) for numerous non-exempt wells were identified; however, none of these wells are registered with ADWR as belonging to Flagstaff. It is unclear why the redundancies existed or why some wells did not have an ADWR 55 No. assigned. AMEC therefore consolidated the NARGFM non-exempt well data and created a new pumping well identification system unique to the Flagstaff Model. To achieve this, the following actions were undertaken:

- Duplicate non-exempt NARGFM wells (wells with the same ADWR 55 No.) with a NARGFM provided ADWR 55 No.: All wells with matching ADWR 55 No.'s were merged into one well. Each new well was assigned a unique "AMEC ID". The pumpage from each NARGFM duplicate well was combined into each new respective AMEC ID well such that all possible pumpage could be captured (regardless of whether pumpage was potentially duplicated). Pumpage data for 2006 through 2010 for this new set of AMEC ID wells was obtained from ADWR's on-line website database (ADWR, 2012b).

- Duplicate non-exempt NARGFM wells sets without a NARGFM provided ADWR 55 No.: All wells without an ADWR 55 No. were assigned their own unique AMEC ID. Because this set of new AMEC ID wells had no associated ADWR 55 No.'s, pumpage data could not be obtained from ADWR's on-line website database. Therefore, AMEC used the last reported pumpage value from the NARGFM pumpage dataset as the annual pumpage volume simulated value for the period 2006 through 2010.

All ADWR registered non-exempt wells constructed after 2005 (for the entire model domain) were also incorporated in the Flagstaff Model. The ADWR 55 No.'s and geographic coordinates for these additional non-exempt pumping wells were provided to AMEC by ADWR (ADWR, 2011 through 2012). Each of these wells were assigned a unique AMEC ID and included in the Flagstaff Model. Pumpage data for 2006 through 2010 for this new set of AMEC ID wells was obtained from ADWR's on-line website database (ADWR, 2012b).

Data for Flagstaff owned wells were provided to AMEC by Flagstaff (Flagstaff, 2009 through 2012). All pumpage data provided by Flagstaff was used in-lieu of the NARGFM data. Historical pumpage data was also obtained from Doney Park, Kachina Village, Mountain Dell, and Forest Highlands for their production wells[4]. Where provided, all pumpage data from these four private water providers was used in-lieu of the NARGFM data.

ADWR Exempt Wells

The Flagstaff Model includes the simulation of all ADWR exempt wells included in the NARGFM. Exempt wells, as determined by the State of Arizona, pump 35 gpm or less and are considered domestic wells for this modeling analysis. The ADWR 55 No.'s and geographic coordinates for all exempt wells constructed after 2005 (for the entire model domain) were provided to AMEC by ADWR (ADWR, 2011 through 2012). Each of these wells was assigned a unique AMEC ID and included in the Flagstaff Model. All exempt wells in the NARGFM were assigned a pumping rate of either 0.33 or 0.5 af/yr. Based on discussions between AMEC and ADWR personnel by (ADWR, 2011 through 2012), all exempt wells in the Flagstaff Model were set to pump at the higher of the two rates (0.5 af/yr) for all years simulated. The NARGFM used 0.33 af/yr for aquifers other than the basin fill (Pool et. al., 2011 [see p. 41]).

ADWR Issued Demands

"Issued" demand was simulated in the Flagstaff Model from data obtained from ADWR (ADWR, 2011 through 2012) for a total of 289 ADWR approved demand applications (included as Appendices A-1 and A-2). The total ADWR issued demand for each permitted allowance was

[4]Additional Flagstaff area water providers were contacted with the same request but none responded.

distributed equally over the parcels listed in the data spreadsheets provided by ADWR. For example, the demand application for "Rivers View Estates" was approved for 35.35 af/yr (Appendix A-1 [see page 8 of 11]). This demand was issued on March 22, 2007 and assigned to Sections 30 and 31 in Township 14 North, Range 5 East. In this case, two new wells were created and each assigned a unique AMEC ID. Each well was placed at the center of the assigned Sections (Sections 30 and 31) and assigned a proportionate pumping rate based upon the number of simulated wells, and the number of Sections the demand was assigned (35.35 af/yr ÷ 2 wells = 17.675 af/yr per well). The start of simulated pumping began in the calendar year for which the respective demand was issued (the beginning of 2007 in this example). The same process was used to simulate all ADWR issued demands.

In addition to the aforementioned 289 ADWR approved "issued" demand applications, seven additional ADWR approved demand applications were provided by ADWR to AMEC for incorporation into the Flagstaff Model (ADWR, 2011 through 2012) (Appendices A-1 and A-2). These included: American Ranch Domestic Water Improvement District, Town of Snowflake, Arizona Water Company in Pinetop/Lakeside, City of Holbrook, City of St. John's, Town of Springerville, and Town of Winslow (Appendices B-1 through B-7, respectively). The ADWR provided well pumpage data that was used to prepare Appendices B-1 through B-7 is provided in Appendix B-8. For the above seven applications, specific instructions were provided by ADWR to AMEC related to which existing ADWR registered wells should simulate the approved demands and how much pumping should be assigned to each well. The ADWR 55 No.'s wells, geographic coordinates, and model simulated pumping rates for the aforementioned seven applications were provided by ADWR (ADWR, 2011 through 2012) to AMEC and incorporated into the Flagstaff Model accordingly.

3.4.8 Boundary Conditions

Boundary conditions for the period 1910 through 2005 were taken from the NARGFM (Pool et. al., 2011). Additional boundary stresses in the Flagstaff Model (i.e., pumping, natural and artificial recharge, ULM and Lake Elaine seepage, etc.) for the period 2005 through 2010 were discussed and presented in previous sections of this report. Boundary conditions for the predictive Scenarios 1 and 2 (both representing year 2001 through 2110) are discussed in **Sections 3.7.1** and **3.7.2** of this report.

3.5 Time Steps

The Flagstaff Model was calibrated to conditions over the transient calibration period (1910 through 2010). A total of 15 stress period were used to simulate this time period, as presented in Table 3.5-1. Identical stress period lengths were used in the Flagstaff Model as the NARGFM for the period 1910 through 2005. One year stress periods were created for the remainder of the Flagstaff Model transient calibration period (2006 through 2010) (Table 3.5-1). This allowed for AMEC to create annual variations in the model input files for pumpage, recharge, etc.

3.6 Model Calibration

After the NARGFM grid was refined and all stresses extended from the end of the NARGFM transient calibration (2005) through the end of the Flagstaff Model transient calibration period (2010), the Flagstaff Model was run to evaluate results against the NARGFM, and against the observation dataset within the Focused Study Area. The end of year 2005 (stress period 10) was selected for the comparison. This was done prior to completing the Flagstaff Model transient calibration (1910 through 2010) so that the grid refinements and stress modifications (pumpage, recharge, etc. from 2005 through 2010) could be fully evaluated.

The December 2005 head distribution in the NARGFM and the re-calibrated Flagstaff Model were generally within 10 feet of each other for all model layers, and mass flow balances were within 1% of each other. Both of these results indicate that NARGFM translation was conducted appropriately with minimal impact on the starting conditions for the Flagstaff transient calibration efforts. The minor differences between the two models as noted above are attributed to the refined grid, revised pumping fluxes (e.g., consolidation of the NARGFM pumping datasets), and the addition of artificial recharge features within the Focused Study Area (e.g., discharges within the Rio de Flag from the Rio de Flag and Wildcat Hill WWTPs).

The transient model calibration for the Flagstaff Model was then conducted for the period 1910 through 2010. An expert interactive approach which included manual calibration as well as parameter estimation using the inverse modeling software PEST (Watermark Numerical Computing, 2011) was performed. Calibrated parameters included the K values of the porous medium and of the springs and streams. Bottom elevations of springs were adjusted at some locations (up to a maximum of 550 feet) where the drain elevation was higher than adjacent observed WLEs to prevent complete drainage (dewatering). Natural recharge rates and aerial distributions were not adjusted during calibration. Therefore, natural recharge (due to precipitation) is conceptualized to be the same between the NARGFM and the Flagstaff Model.

3.6.1 Calibration Targets

The model was calibrated to all target WLEs located within the Focused Study Area, which totaled 2,941 targets[5] from a total of 950 wells. All target identifications (ADWR 55 No.'s), XY coordinates, and observed WLE data was obtained from ADWR's on-line website for wells contained within the Groundwater Site Inventory (GWSI) Database (ADWR, 2012b). The 2,941 targets include the following number of observed WLEs for the time periods indicated below:

Year or Decade	No. of Observed WLEs
1939	1
1940s	40
1950s	111
1960s	278

[5]The term "target" in this section of the report refers to a single WLE measurement taken from any given well. The targets were obtained from the NARGFM dataset and augmented with new wells (constructed and registered with ADWR post-2005) where water level was available from ADWR's GWSI database (ADWR, 2012b).

1970s	565
1980s	170
1990s	848
2000s	928

A subset of the 2,941 targets, consisting of 739 targets from a total 37 ADWR "Index" wells, was then used to further evaluate the transient calibration. Typically, ADWR Index wells are visited once each year by ADWR field staff to obtain a long-term record of WLE (groundwater) fluctuations. ADWR Index wells are considered more reliable for calibration than the larger complete set of targets discussed above because they have multiple WLE measurements (**Section 3.6.2** provides additional discussion on this subject). Spring fluxes within the entire Flagstaff Model domain were also evaluated during transient calibration at major spring and stream gauging locations. **Section 3.6.3** provides additional discussion on this subject.

Calibration of the Flagstaff Model was conducted by comparing measured WLEs and groundwater flux with simulated WLEs and groundwater flux using the following methods:

- Transient calibration of simulated WLEs to groundwater elevations measured during the 1910 through 2010 transient calibration period:
    - Target WLEs were evaluated at all wells located within the Focused Study Area to minimize large errors in simulated WLEs throughout the Flagstaff Model domain. Evaluations included residual statistics, regression trends and residual maps to evaluate and reduce simulated bias;
    - Measured versus simulated hydrographs were compiled for the smaller subset of targets (the 37 ADWR Index wells) to evaluate observed versus simulated WLE trends; and,
    - The average residual head error in the C Aquifer in the vicinity of Flagstaff, RGR, and ULM was minimized; these areas are the focus of this study and represent the most significant locations of future groundwater development and management for Flagstaff.

- A location map showing the 45 springs (some of which represent stream gaging station locations along washes, streams or rivers) used to compare simulated fluxes to observed data is provided as Figure 3.6.1-1. Observed data at springs within the Flagstaff Model is sparse, and typically only one measurement value in time is available at most of the springs or streams within the entire Flagstaff Model domain. A more detailed discussion of spring target evaluations is provided in **Section 3.6.3** of this report;
- Satisfaction of global water mass balance (i.e., simulated groundwater flux into the model domain must equal simulated groundwater flux out of the model domain); and,
- Sensitivity analyses of the numerical groundwater model to hydraulic conductivities, storage properties, and river/drain conductances were performed to evaluate the impact of uncertainties in their modeled values on WLEs and drawdown.

3.6.2 Groundwater Levels and Flow Directions

The simulated groundwater elevation contours for December 2010 (representing the end of the transient calibration period) for Flagstaff Model layers 1, 2, and 3 in the Focused Study Area are provided in Figures 3.6.2-1, 3.6.2-2 and 3.6.2-3, respectively. The flow directions are generally in accordance with observations, and the documented groundwater divides (Bills et. al., 2007; Hart et. al., 2002) located south and southwest of Flagstaff (present only in model layers 2 and 3), and north-northwest of Flagstaff (present only in model layer 3) are well represented by the Flagstaff Model.

Figures 3.6.2-1, 3.6.2-2 and 3.6.2-3 show the groundwater level differences ("residuals") as positive (meaning simulated groundwater levels are higher than observed) where red or orange, and negative (meaning simulated groundwater levels are lower than observed) where blue or green. In model layer 1 the residuals are small and balanced, both positive and negative average residuals, ranging from -61 to +85 feet, except in the northeastern corner of the Focused Study Area (far removed from Flagstaff or RGR), where errors are larger and simulated WLEs are consistently low (ranging from an average of 3,638 to 4,462 feet amsl).

In model layer 2, the residuals are also small and balanced except for locations near steep ridges where large changes occur over small lateral distances. Larger residuals are also noted for target wells located within one grid-block or in adjacent grid-blocks that have widely varying observed values, thus making them difficult to precisely calibrate against. These larger residuals occur due to complex geology, stratigraphy, and sub-grid scale heterogeneities not captured by the horizontal and vertical discretization. The predictions of the model are not affected by this however, because the model is not examining drawdown at that fine a spatial scale (scales of a mile or more and not 100s of feet, which would be incompatible also with the model time scales of decades). The same observations as provided above for model layer 2 are also noted in model layer 3 (representing the R Aquifer). Average residuals in model layer 2 range from -171 to +233 feet, and in model layer 3 range from -214 to +139 feet.

As previously discussed, two sets of residual summary statistics are presented in this section:

- A summary statistics for all targets located within the Focused Study Area (2,941 targets from 950 wells), where at least one WLE is available per well over the entire transient calibration period; and,
- A summary statistics for ADWR Index wells located within the Focused Study Area (739 targets from 37 ADWR Index wells), where more than one WLE is available per well over the entire transient calibration period.

Groundwater Elevations

The summary statistics for the transient calibration against all observed WLEs within the Focused Study Area are provided in Table 3.6.2-2. The mean residual is approximately +10 feet indicating a balanced overall calibration. The maximum and minimum residuals and residual standard deviation while very large (+1,052 feet, -2,946 feet, and +173 feet, respectively), the normalized statistics (with respect to the total range in WLEs across the available/selected measurements) are low and within reasonable bounds of calibration. The regression line between observed and simulated WLEs for all target wells within the Focused Study Area is shown on Figure 3.6.2-4. The results are noted to lie close to the linear regression line with a correlation coefficient (R^2) of 0.9769.

Table 3.6.2-3 shows the summary statistics for the calibration against WLE measurements at the 37 ADWR Index wells located within the Focused Study Area. The mean residual from this set of targets is approximately +17 feet, indicating a slightly positive overall bias, which is in agreement with the mean residual over all targets (Table 3.6.2-2). The normalized statistics against the 37 ADWR Index wells is also low and within reasonable bounds of calibration. Figure 3.6.2-5 shows the regression line between observed and simulated WLEs at the ADWR Index wells in the Focused Study Area. The regression is good with a correlation coefficient (R^2) of 0.9746. Observed versus model simulated hydrographs for the 37 ADWR Index wells in the Focused Study Area are shown on Figures 3.6.2-6a 3.6.2-6b, and 3.6.2-6c for model layers 1, 2, and 3, respectively.

Saturated Thickness

Figures 3.6.2-7 and 3.6.2-8 show the model calibrated (December 2010) saturated thickness within the Focused Study Area for model layers 2 and 3, respectively. Model layer 1 was not evaluated because it is absent below (Figure 3.3.2-5), and does not represent the primary aquifer (the C Aquifer) for wells drilled at RGR, or for future planed production wells at RGR

A 10-mile radius around Flagstaff and RGR was selected as comparison criteria to look at model predicted impacts for the two predictive Scenarios (1 and 2). Comparisons of model predicted impacts associated with pumping at the Flagstaff wells and the TRG wells were made based on the results, most of which appears to take place at a radius less than the 10-mile radius referenced herein. In model layer 2, the model calibrated (December 2010) saturated thickness within a 10-mile radius of Flagstaff ranges from approximately 359 to 4,094 feet, and within a 10-mile radius of RGR ranges from 675 to 3,370 feet (Figure 3.6.2-7). All Flagstaff wells and TRG wells as presented in this report were simulated with pumping entirely from model layer 2 (the C Aquifer).

In model layer 3, the model calibrated (December 2010) saturated thickness within a 10-mile radius of Flagstaff ranges from approximately 984 to 2,487 feet, and within a 10-mile radius of RGR ranges from 1,909, to 3,937 feet (Figure 3.6.2-8). No Flagstaff or TRG wells as reported herein simulated pumping from model layer 3 (the R Aquifer).

3.6.3 Spring and Stream Flows

The Flagstaff Model was evaluated against spring, river, and wash flows within and around the Focused Study Area for the model transient calibration period (1910 through 2010) at the 46 flow target locations shown on Figure 3.6.1-1. Table 3.6.3-1 provides the observed versus model simulated spring, river, or wash flow rates for all 46 flow targets. All but three of the observed flow targets values are single time “snapshots” (one flow recorded during one singular event). The statistics provided in Table 3.6.3-1 compare the sums of the average observed versus model simulated flows for flow targets located inside the Focused Study Area, outside the Focused Study Area, and both areas combined (model-wide).

Based on the statistical results, the difference between the average observed versus modeled simulated flows is +16% within the Focused Study Area, -1% outside of the Focused Study Area, and +15% model-wide (Table 3.6.3-1). These are considered excellent calibration statistics given the limited availability of observed spring flow data during the transient calibration period (1910 through 2010).

3.6.4 Mass Balance

MODFLOW iteratively calculates a solution for the numerical groundwater model by minimizing the flow error at every time step. The global mass balance calculated by MODFLOW is included in the list file. The components of the water mass balance terms for the transient calibration period (1910 through 2010) for the Flagstaff Model (domain-wide) are shown on Figure 3.6.4-1 and summarized in Table 3.6.4-1. The water mass balance terms for the end of the transient calibration period (December 2010) within the Focused Study Area are summarized in Table 3.6.4-2.

As shown in Table 3.6.4-1, the cumulative mass balance error between the calculated inflows and outflows for the calibration period (1910 through 2010) for the entire Flagstaff Model domain was negligible (0.04%). As shown in Table 3.6.4-2, the mass balance error between the calculated inflows and outflows at the end of the transient calibration period (December 2010) within the Focused Study Area was 0.14%. As illustrated on Figure 3.6.4-1 and presented in Tables 3.6.4-1 and 3.6.4-2, the greatest fluxes into the model (listed in descending order) are: recharge from precipitation; boundary inflows; recharge from storage; recharge from rivers, streams, and springs; and, artificial recharge (lakes, WWTPs, golf courses, etc.). The greatest fluxes out of the model (listed in descending order) are: discharge from rivers, streams, and springs; boundary outflows; pumping wells, storage out, and ET.

3.6.5 Model Simulated Water Budget

Table 3.6.5-1 provides a summary of the calibrated transient Flagstaff Model (domain-wide) water mass balance terms at the end of 2005. As previously discussed in **Section 3.1**, the Focused Study Area includes portions of five different basins and/or sub-basins within the NARGFM. As such, a comparison between water budgets of the Flagstaff Model and the NARGFM were done for the year 2005 (corresponding to the end of the NARGFM transient calibration).

According to the NARGFM report, total inflows and outflows to the NARGFM in 2005 are 1,395,700 and 1,857,000 acre feet, respectively, resulting in a mass balance error of approximately 25% (Pool et. al., 2011 [see Table 2]). In comparison, the total inflows and outflows to the Flagstaff Model in 2005 are 1,364,956 and 1,364,566 acre feet, respectively (Table 3.6.5-1), resulting in a mass balance error of approximately 0.03%. The variability in the outflow components, according to the NARGFM report, is attributed to the “net rate of groundwater storage change” (loss) (Pool et. al., 2011, Table 2). When weighted and evaluated with the other transient calibration tools as previously presented in **Sections 3.6.1** through **3.6.4** of this report, the outflow variance between the two models has little to no impact on the overall calibration results of the Flagstaff Model.

3.6.6 Calibration Summary

The following summarizes the calibration results for the Flagstaff Model:

- Observed flow directions and groundwater divides are well represented (matched);
- Errors that were generally unbiased in space;
- WLE residuals were generally small in the C Aquifer in the vicinity of Flagstaff, RGR, and Lake Mary, all of which are significant locations of groundwater management for Flagstaff;
- The model calculated spring, river, or wash flow targets (46 total) were within 10% of observed flows for the transient calibration period (1910 through 2010);
- The cause of the large errors in the Flagstaff Model were explored and attributed to large variations in hydrogeologic properties (e.g., abrupt changes in K values due to complex geology, stratigraphy, and sub-grid heterogeneities), which are in the Flagstaff Model to represent significant hydrogeologic features (e.g. groundwater divides, the Mogollon Rim, sub-basin boundaries, large structural faults, etc.) The predictions of the model are not affected however because the model is not examining drawdown at that fine of a scale. The large residuals are due to the challenge of adequately characterizing the governing hydrogeologic features that control flow. Also, large residuals may be caused by structural or conceptual limitations (i.e. the understanding of how fractures are oriented and connected.);
- The calibration statistics were acceptable; and,
- The correlation coefficient was excellent.

The Flagstaff Model also has good calibration to spring, river, and wash flows (see Figure 3.6.1-1. Table 3.6.3-1), and negligible mass balance errors both within the Focused Study Area and model-wide (see Tables 3.6.4-1 and 3.6.4-2). The spatial scale of the domain was sufficiently refined to address basin-wide issues on water availability, and the temporal scale was adequate to address long-term water management questions. Therefore, the Flagstaff Model is considered well calibrated to WLEs and water fluxes, and is an appropriate tool for evaluating the 100 year availability of water in support of the Flagstaff Application.

3.7 Predictive Model Results

The calibrated transient Flagstaff Model was used to evaluate two different water planning strategies for Flagstaff (Scenarios 1 and 2). Both Scenarios are discussed further below, along with the limitations of the Flagstaff Model.

The Flagstaff Model Scenarios 1 and 2 consisted of varying pumping at 39 Flagstaff production wells. These wells are within or immediately adjacent to Flagstaff, and within the RGR property boundaries. The 39 production wells simulated, as shown in Figure 3.7-1, include:

- 26 existing Flagstaff wells:
  - Eight wells located within the interior portion of Flagstaff (the “Local Well Field”);
  - Eight wells located adjacent to Lake Mary (the “Lake Mary Well Field”);
  - 10 wells located in the Woody Mountain area (the “Woody Mountain Well Field”); and,
- 13 model simulated wells at RGR (the “TRG wells”).